Monitoring near-surface thermal properties in conjunction with energy and moisture budgets to facilitate the optimization of ground-source heat pumps in the glaciated Midwest

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By exploiting the near-surface heat reservoir, ground-source heat pumps (GSHP) represent an important renewable energy technology that can be further developed by establishing data sets related to shallow (<100m) thermal regimes. Although computer programs are available for GSHP installers to calculate optimal lengths and configurations of ground-coupling geothermal systems, uncertainties exist for input parameters that must first be determined for these models. Input parameters include earth temperatures and thermal properties of unconsolidated materials. Furthermore, thermal conductivity of sediments varies significantly depending on texture and moisture content, highlighting the need to characterize various unconsolidated materials under varying soil moisture regimes. Regolith texture data can be, and often are, collected for particular installations, and are then used to estimate thermal properties for system design. However, soil moisture and temperature gradients within the vadose zone are rarely considered because of the difficulty associated with collecting a sufficient amount of data to determine predominant moisture and temperature ranges.

Six monitoring locations were chosen in Indiana to represent unique hydrogeologic settings and near-surface glacial sediments. The monitoring approach includes excavating trenches to a depth of 2 meters (a typical depth for horizontal GSHP installations) and collecting sediment samples at 0.3-meter intervals to determine thermal conductivity, thermal diffusivity, and heat capacity in the laboratory using the transient line heat source method. Temperature sensors are installed at 0.3-meter intervals to continuously measure thermal gradients. Water-content reflectometers are installed at 0.3, 1, and 2 meters to determine continuous volumetric soil moisture. In-situ thermal conductivity and thermal diffusivity are measured at 1.5 meters using a differential temperature sensor that measures radial differential temperature around a heating wire. Micrometeorological data (precipitation, insolation, ambient air temperature, relative humidity, and wind speed) are also collected to determine surface energy and water budgets that drive fluxes of energy and moisture in the shallow subsurface. By establishing continuous, year-round data, fluctuations in seasonal energy budgets and unsaturated zone soil moisture can be considered such that GSHP system designers can establish accurate end members for thermal properties, thereby optimizing the ground-coupling component of GSHPs. These data will also provide empirical controls such that soil moisture and temperature regimes can be spatially distributed based on mapped soil units and hydrogeologic settings in Indiana.

Rationale Behind Monitoring Network

- Computer programs exist for ground-source heat pump (GSHP) installers to calculate optimal loop lengths for ground-coupling systems
- Uncertainties exist for input parameters such as earth temperatures, soil thermal conductivity (λ) and thermal diffusivity (D)
- Based on geotechnical parameters for unconsolidated sediments, required trench lengths for horizontal GSHPs can range between 70 and 170 meters per ton of heating demand (Figure 1)
- Land area requirements can vary between 140 and 280 m^2 per ton

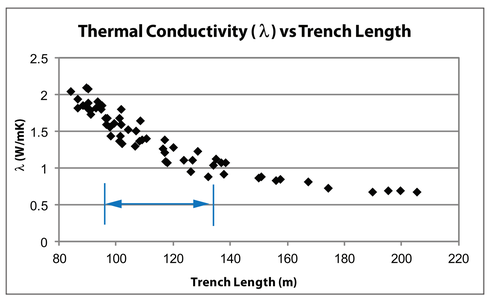

Figure 1. Thermal conductivity of unconsolidated sediments plotted vs. calculated horizontal trench length for a 1.25-ton system capacity in heating mode. Trench lengths determined using LoopLink ground-source heat pump design software. Arrows indicate the range of trench lengths that would result from thermal conductivities measured at site #4.

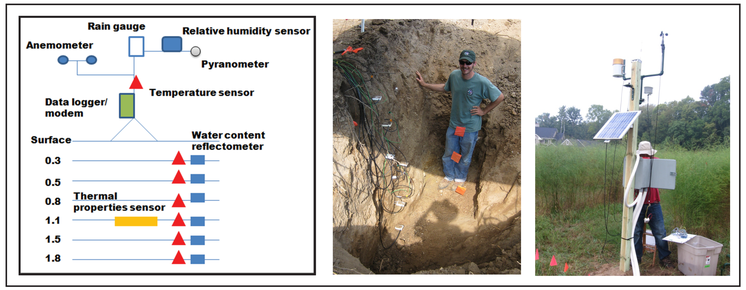

Figure 3. Instrument array at each monitoring site

Table 1. Geologic settings, sediment textures, and bulk densities at each site

Site #	Geologic Setting	Sediment Texture	Bulk Density (g/cm^3)
1	Alluvial terrace	Silt loam	1.32 - 1.58
2	Till plain	Site not yet installed	Not yet determined
3	Moraine crest	Clay loam	1.41 - 1.79
4	River terrace composed of supraglacial till	Sandy clay loam	Not yet determined
5	Moraine crest	Silty clay	1.64 - 1.80
6	Outwash terrace at margin of moraine and former meltwater channel	Sandy loam	1.46 - 1.71

Data collection aimed at establishing:

1. Near-surface, year-round temperature gradients (energy budget)
2. Continuous measurements of thermal conductivity and thermal diffusivity such that seasonal variations can be considered
3. Continuous soil-moisture data and therefore end members for various unconsolidated sediments and hydrogeologic settings (water budget)

Characterizing Water Budgets

- -Precipitation
- -Penman evapotranspiration
- -Soil moisture content at 0.3-m intervals

Characterizing Energy Budgets

- -Air temperature
- -Incoming solar radiation
- -In-situ temperature measurements at 0.3-m intervals

Thermal Conductivity Sensors and Calibrations

1. Decagon KD2 Pro (transient line heat source)
   -laboratory and spot field measurements
2. Hukseflux TP01 (radial differential temp. around heating wire using two thermopiles)
   -in-situ installation and continuous data collection

Sensor thermal conductivity calibrated using unconsolidated materials with known values:

- -Glycerin (0.285 W/mK)
- -0.5% agar gel (0.598 W/mK)
- -5% agar gel (0.554 W/mK)
- -Dry Ottowa sand (0.332 W/mK)
- -Saturated Ottowa sand (3.31 W/mk)

Since the Hukseflux TP01 sensors were understimating thermal conductivity of standard samples, a transform was developed using six additional material measurements and developing a linear relationship with the KD2 Pro TR-1 sensor measurments (Figure 5).

Figure 7. KD2 Pro sensors installed adjacent to Hukseflux sensor at site #3 in order to compare in-situ measurements

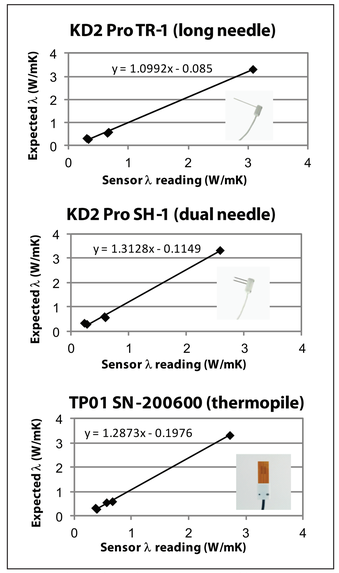

Figure 4. Thermal conductivity sensor calibrations

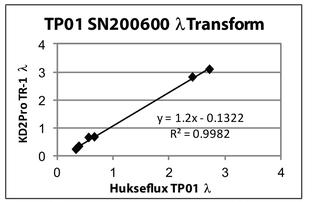

Figure 5. Transform equation developed for one of the Hukseflux TP01 sensors

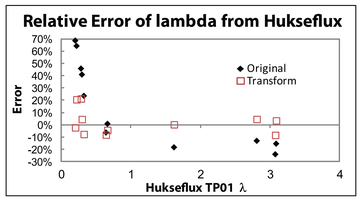

Figure 6. Error analysis for four calibrated Hukseflux sensors

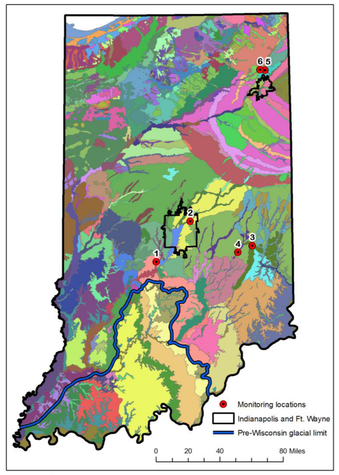

Figure 2. Site locations relative to hydrogeologic settings mapped by Fleming et al. (1995)

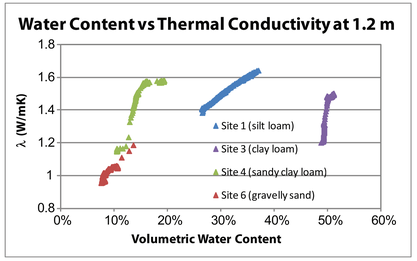

Figure 10. Plot showing the varying dependence of thermal conductivity on moisture content at four sites

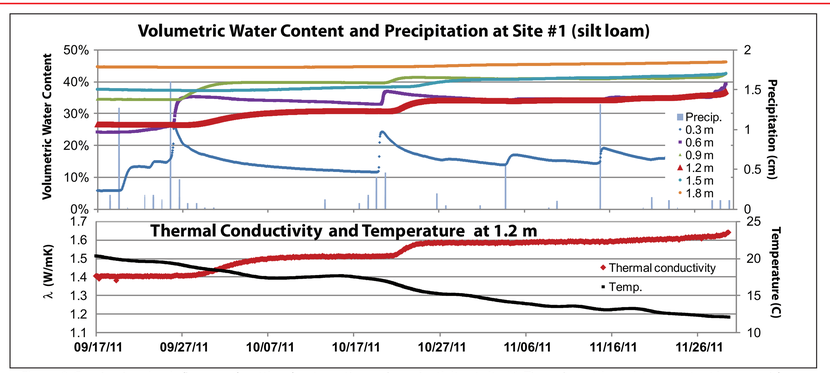

Figure 8. Graphs showing influence of wetting fronts on thermal conductivity at site #1. The volumetric moisture content increased from 27 to 34% at 1.2 meters and resulted in a 13% increase in thermal conductivity at that depth.

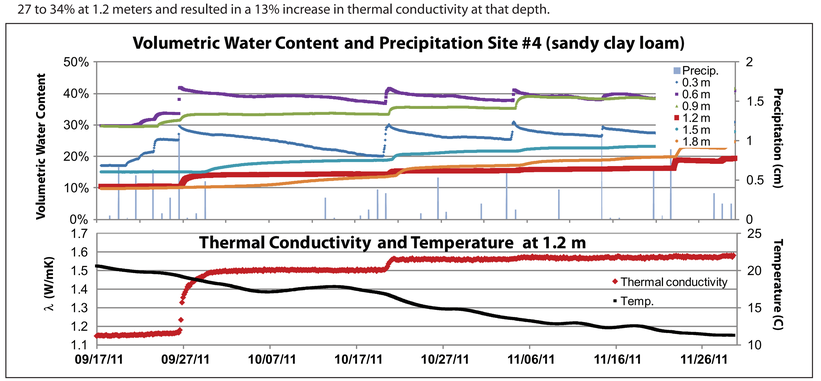

Figure 9. Graphs showing influence of wetting fronts on thermal conductivity at site #4. The volumetric moisture content increased from 10 to 15% at 1.2 meters and resulted in a 35% increase in thermal conductivity at that depth. Trench lengths for ground-coupling loops vary significantly based on this range in thermal conductivity as shown in Figure 1.

Preliminary results

- -wetting fronts are propogating to 1.2 m depth and prominently influencing thermal properties (both thermal conductivity and temp.)
- -data at site #4 indicate that seasonal fluctuations in thermal conductivity can be as much as 35%

References

Fleming, A. H., Bonneau, P., Brown, S. E., Grove, G., Harper, D., Herring, W., Lewis, E. S., Moeller, A. J., Powell, R., Reehling, P., Rupp, R. F., and Steen, W. J., 1995, Atlas of hydrogeologic terrains and settings of Indiana, Final Report to the Office of the Indiana State Chemist, Contract No. E005349-95-0, Indiana Geological Survey, Open-File Report 95-7.

Project sponsors and collaborators

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